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A Sensitivity Based Design Environment

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THE AIR FORCE
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1 February 1998 - 31 January 1999

by

John A. Burns, Director
Air Force Center for Optimal Design and Control

Wright House / West Campus Drive
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061-0531

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This report contains a summary and highlights of the work funded by the Air Force under AFOSR Grant F49620-98-1-0246, titled "A Sensitivity-Based Design Environment". This effort, funded under the Defense University Research Instrumentation Program (DURIP), was conducted by the Center for Optimal Design and Control (**CODAC**), at Virginia Tech during the period 1 February 1998 - 31 January 1999.

The objective of the grant was to assemble the computational facilities to implement a sensitivity-based design environment. In recent years researchers at **CODAC** have developed mathematical foundations and a computational framework for the rapid calculation of design-sensitivities for aerospace applications. Implementation requires approximate solution of certain linear partial differential equation. In aerodynamic applications, for example, these solutions describe in linear approximation how the flow will change with a given change in a (geometric) design parameter. We have acquired an SGI Origin 2000 computer with 16 processors and two SGI Octane workstations to provide the computational platform for these calculations.

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Chapter 1

Introduction

This grant was awarded under the Defense University Research Instrumentation Program (DURIP) and has provided support for equipment to enhance the capabilities of the **PRET- CODAC** researchers to develop and utilize tools that will facilitate engineering design. We have acquired a powerful computational platform that is being used for development of interactive design tools for aero–propulsion systems, as well as in our work on scientific computation/visualization,

The Air Force Center for Optimal Design And Control (**CODAC**), established in 1993, addresses a number of technological thrusts related to these key components. **CODAC** researchers have made significant progress in these areas and our industrial partners: AeroSoft, BEAM Technologies, Boeing Defense and Space Group, give us a proven team of scientists and engineers from small high-tech firms and major aerospace companies. The research group at Virginia Tech has been at the forefront of the development of sensitivity methods for optimal design, with applications to shape optimization for fluid flow management. AeroSoft provides expertise in computational methods for optimization and for simulation of fluid dynamics.

CODAC is funded by the Air Force Office of Scientific Research through the Air Force Program for Research Excellence and Transition (*PRET*) under (Grant AFOSR–49620–96–1–0329). Dr. John A. Burns, Hatcher Professor of Mathematics at VPI & SU, is the Director of **CODAC** and principal investigator on the project. Dr. Marc Jacobs, AFOSR/NM is the technical monitor. **CODAC** is located within the Interdisciplinary Center for Applied Mathematics (**ICAM**) at Virginia Tech. Dr. Terry L. Herdman, Professor of Mathematics at VPI & SU,is the Director of **ICAM**.

Chapter 2

Objectives

2.1 Research Component

A great deal of our work is focused on control and design of fluid, structural, thermal and coupled fluid/structure/thermal systems. Procedures we have developed for distributed-parameter design retain the infinite-dimensional nature of the problem and introduce discretization only as a last step. In particular, we have developed efficient numerical schemes for computing certain design sensitivities. We are working jointly with researchers at the Boeing Defense and Space Group and AeroSoft Inc. on several projects wherein these design sensitivities are computed and used in a design environment. Such sensitivities can be used in several ways.

Firstly, the sensitivity information can be displayed to the designer in much the same way that flow information is now displayed. This new information will indicate not simply the characteristics of the current design but also how the flow properties will change as the design is altered. Such information will aid the designer, in that it provides a first-order estimate of the effects of a design change.

Distributed flow sensitivities are also useful in optimization-based design since they may be used for efficient calculation of cost and constraint gradients. Thus, on option, the designer may choose to execute one or more cycles of such a design-optimization algorithm.

The design tools we have in mind are applicable to a wide-class of continuum problems including flows, structures and material processing. These tools would enable a designer to more quickly arrive at an efficient design configuration.

The research has wide applicability and promises considerable payoff in aerospace design applications. In order to provide focus for the research and to expedite its transition to industrial use, the *Center* has developed research partnerships with the following groups:

- Boeing Defense and Space Group (BDSG), Seattle, WA

  E.L. Roetman, J. Lee and W. Herling

  Tools for Optimization Based Wing-Body Design

- AeroSoft Inc., Blacksburg, VA

  W. McGrory and A. Godfrey

  Sensitivity Calculation for High-Speed Chemically Reacting Flows

- BEAM Technologies, Needham Heights, MA

  G. Berkooz

  Sensitivity Enhancements in the PDESolve$^{\text{TM}}$ Environment

The research program integrates scientific and computational tools developed at AeroSoft, BEAM Technologies, Boeing and Lockheed Martin with new sensitivity techniques and optimization algorithms developed at Virginia Tech and Cornell. The project will produce a computational framework and related computer tools that engineers can use to efficiently model, design and optimize aerospace systems. The focus of the program includes fundamental research in sensitivity-based methods for optimal design of complex aerospace systems governed by partial differential equations. In addition, our team is structured to promote the transition of this basic research to Air Force laboratories and to industry.

2.2 Educational Component

The Interdisciplinary Center for Applied Mathematics (**ICAM**) was formed in August 1987 to to promote and facilitate interdisciplinary research and education in applied mathematics at Virginia Polytechnic Institute and State University. The goal of **ICAM** is to enhance the historical links among mathematics, engineering and the sciences. Core participants in **ICAM** are committed to providing interdisciplinary research experience for both graduate and undergraduate students. The equipment purchased under this grant is available for use by qualified students in their research and in their formal studies.

Chapter 3

Status and Highlights

3.1 Equipment Purchased

The principal equipment purchased under the grant were an SGI Origin 2000 with 16 R10000 processors (195MHz) and two SGI Octane workstations. Along with the University cost-sharing we were able to purchase

- SGI Origin 2000 with 16 R10000 processors and 2 GB of memory (Silicon Graphics)
- An additional 16 GB of third-party memory (Dataram)
- Cray Cross-Link cables
- Additional disk-drives (45 GB)
- SGI Octane Workstations (2)
- 12.5kVa uninteruptible power supply (Best Power)
- ATM boards and fiber connection to a local ATM network (ForeSystems)

This equipment has been integrated into the **ICAM** computer network.

3.2 Current Computing Facilities

ICAM houses a heterogeneous Unix system with file-sharing under a Network File System (NFS). The Unix system currently consists of the following components:

1. Our main file server is four processor SUN-1000, with 128MB internal memory. An external cabinet houses approximately 100GB of disk space through a SCSI connection.
2. Our graphics workstations include a Silicon Graphics Onyx2 with Infinite Reality graphics and four R10000 processors, four single-processor (R10000) Octane workstations, and an SGI IRIS 4D/310 graphics workstations. Two SGI-Indigo2 workstations feature R8000 processors, 128MB of memory and Extreme graphics.

3. Our main computational platform is a SGI Origin 2000 with 16 R10000 processors and 18GB of memory (`origin.icam.vt.edu`). This machine, which operates in the range of 10 GF, supports interactive use and batch use under the Network Queuing System (NQS). The machine can be dedicated to a single-user for particularly challenging computations.

4. Additionally, we support two DEC Alpha 3000/600 computers with 256MB of memory. A third DEC AlphaServer 2100 is a dual-processor machine with 512MB of memory.

5. The system is connected via an Asynchronous Transfer Mode network (ATM - OC3, 155 Mb/s) and by switched-Ethernet.

6. In addition to the dedicated monitor/keyboard for each platform, the computers can be accessed via the switched-Ethernet. The *Center* currently has ten (10) Pentium II–based personal computers (two in faculty offices and eight for public use) and six (6) Power-Mac machines (two in a faculty offices).

Chapter 4

Accomplishments

Advances in computational arts - analysis, software and hardware - have greatly enhanced the process of analyzing proposed design concepts. Such advances have occurred in virtually all engineering disciplines but especially in those related to advanced aerospace systems. While such analysis tools are important, an even bigger payoff awaits the development of advanced tools for design synthesis. The equipment purchased under this grant has enhanced our abilities to do fundamental research on the development of interactive design tools.

4.1 Sensitivity to Airfoil Rotation: Comparing Two Formulations

In aerodynamic design, CFD tools are used to predict flow properties for a given design by numerically approximating the solution of a nonlinear boundary-value-problem (BVP). Since analyses of nonlinear phenomena commonly employ a local linearization, it is of interest to construct such a linearization for aero-prediction applications. One approach to this problem leads to a linear BVP - the solution of this problem is a flow sensitivity and describes, in linear approximation, how the flow field will vary as a (scalar) design parameter is changed.

Consider a particular application of these ideas to two-dimensional, compressible, inviscid flow (Euler equations). The boundary conditions include specification of the incoming, far-field flow and the usual no-penetration condition at the airfoil's surface. It's intuitively clear that the nature of the flow depends on the angle-of-attack - the angle between the incoming velocity and the chord line (say) of the airfoil. This angle can be altered by changing the incoming flow direction or by changing the orientation of the airfoil. In the context of the linear sensitivity problem the former leads to a non-homogeneous boundary condition only at the far-field, while the latter has non-homogeneous boundary data only at the solid surface.

Results from numerical solutions of these two problems are displayed in Figures 4.1 and 4.2. The colors show the variation in pressure-sensitivity, and while the distributions are similar they are quite different along the leading-edge of the body. The flow-velocity-sensitivities are depicted by the streamlines and appear to be quite different in the two cases.

The pressure sensitivities displayed in the Figures 4.1 and 4.2 can be interpreted as *partial* derivatives of the pressure field with respect to the parameters (*i.e.* α, θ, respectively). In the case of the θ variable, a change in it induces chain-rule alterations in the *surface* pressure because the surface points are displaced in the flow-field as θ varies. Thus, in calculating the change in *surface* pressures one must account for this additional dependency. Shown in Figure 4.3, is a comparison of the surface pressure sensitivity computed by the two methods. It is believed that the small differences arise from the fact that the far-field boundary conditions are applied at a finite-distance from the airfoil.

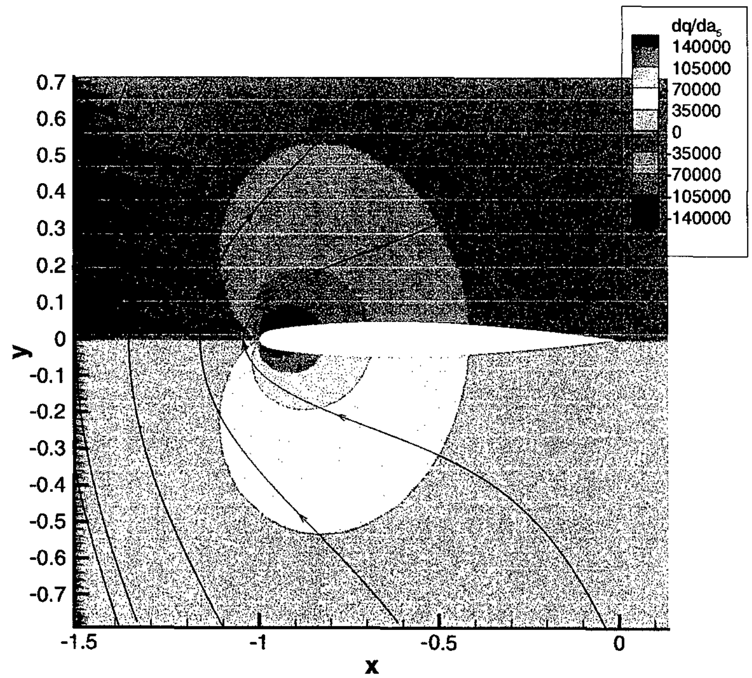

Figure 4.1: Pressure and velocity vectors-sensitivity for a far-field change.

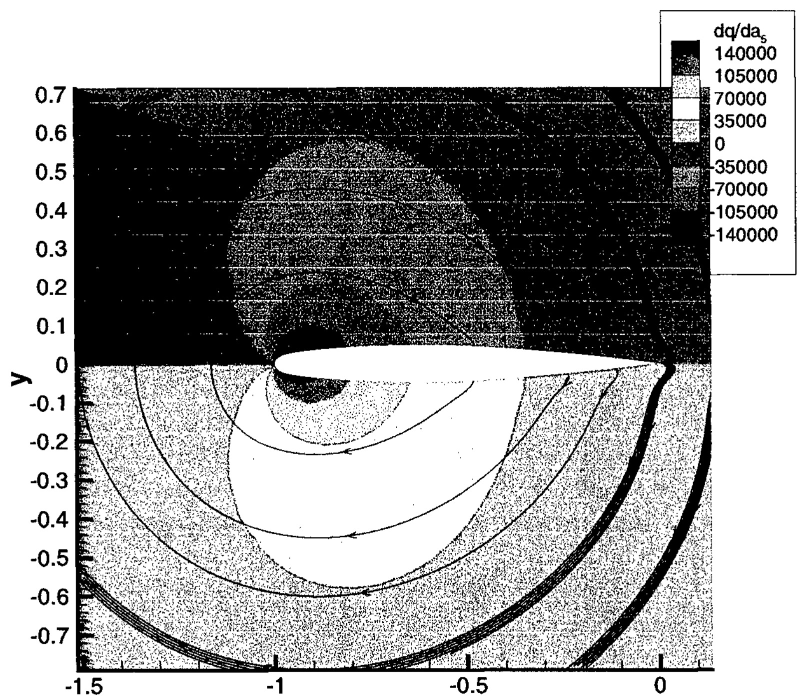

Figure 4.2: Pressure and velocity vectors-sensitivity for an airfoil rotation.

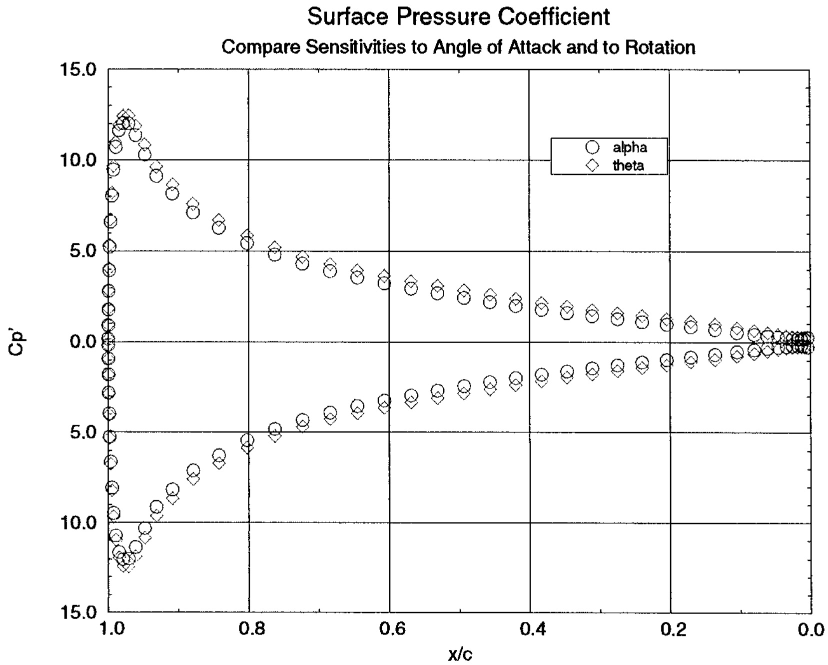

Figure 4.3: Sensitivity of Surface-pressure Coefficient

4.2 A Fundamental Study of Emulsification Jie Li and Yuriko Y. Renardy

Emulsions arise in a wide range of industrial applications, in materials processing, waste treatment, and pharmaceuticals. In order to apply the emulsion technology, one must control and manipulate the rheology of an emulsion and its microstructure. In slow shear flow, the behavior of the emulsion is characterized by the volume fraction of the dispersed phase, the dispersed to continuous phase viscosity ratio, and a capillary number. The capillary number measures the effect of the viscous stresses that deform a bubble *vs* the restoring effect of interfacial tension. Investigations of two-fluid dispersions have been performed on the SGI Origin 2000 machine at **ICAM**. This work includes the study of shear-induced rupturing of a viscous drop. Unlike previous works, which use boundary integral methods and are for zero Reynolds numbers, the present scheme handles both zero and higher Reynolds numbers. The dynamic process that leads from one large drop to smaller drops has been an open question which are studied numerically as an initial value problem. The numerical scheme is based on the volume-of-fluid method developed by Jie Li and Stephane Zaleski (University of Paris VI). The computational flow schematics is shown in Figure 4.4.

These computations achieved 80% efficiency with a parallelized code. Figure 4.5 shows the topological evolution of a cross-section of the viscous liquid drop under high shear, breaking into daughter drops at times 0, 10s, 30s, 45s, 50s, and 70s. This work is on-going.

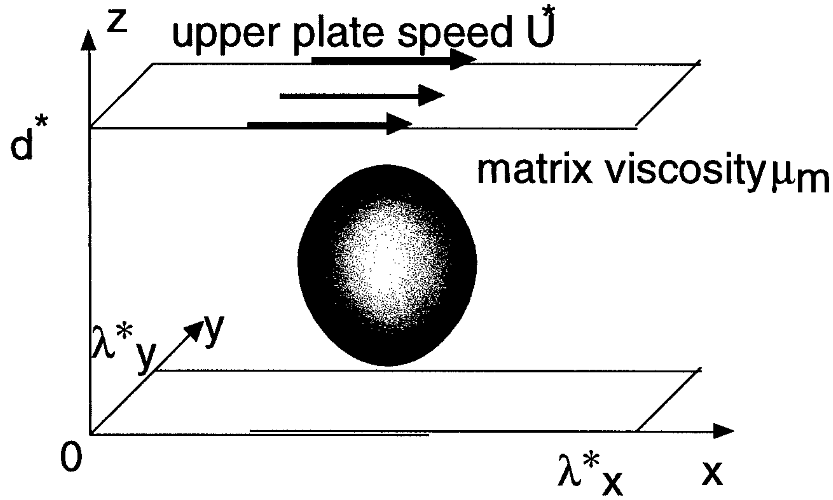

Figure 4.4: Flow schematics. The computational domain is spatially periodic in the x and y directions with wave-lengths λ_x^* and λ_y^*, respectively. Plate separation is d^*. The upper wall moves with velocity $(U^*, 0, 0)$, while the lower wall is at rest. The drop radius is a, and the drop viscosity is μ_d. The matrix viscosity if μ_m.

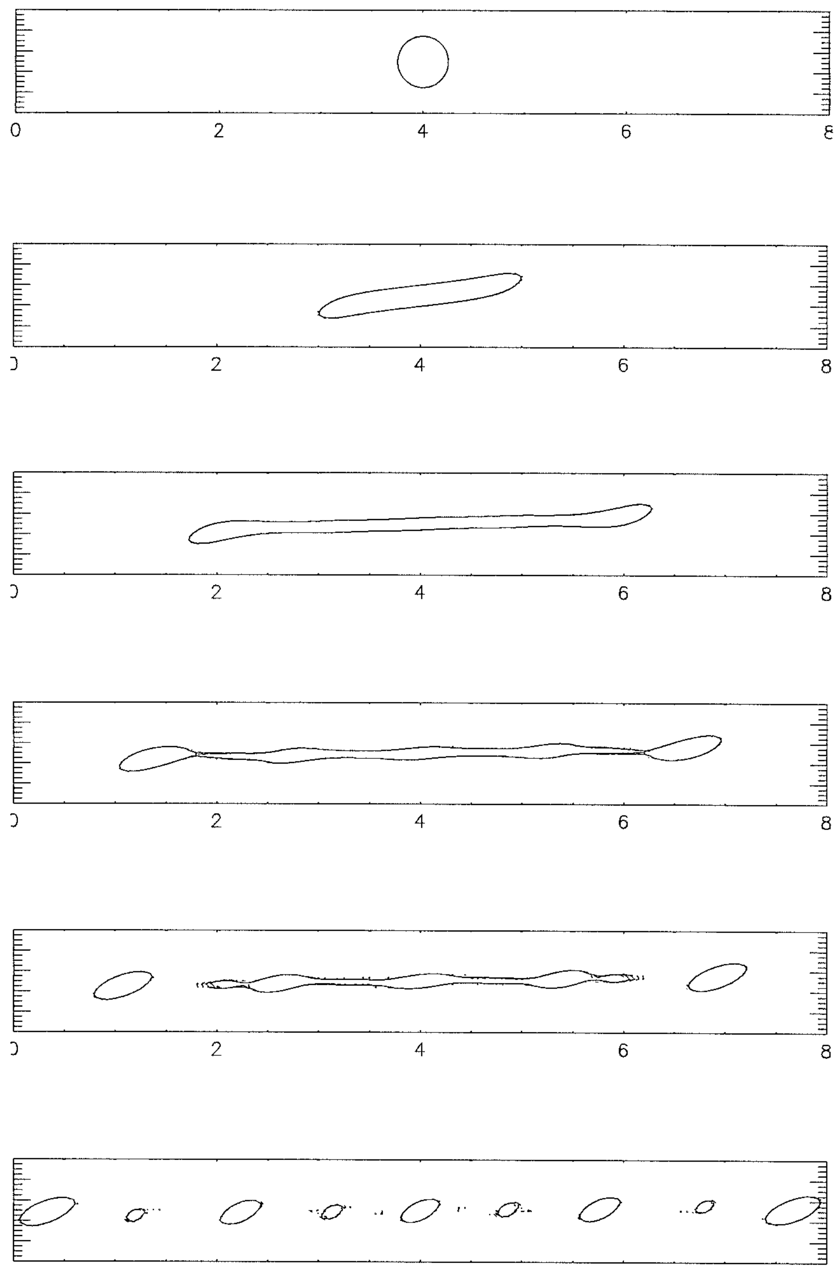

Figure 4.5: Shear rupturing a drop at capillary number 0.45.